Maize Temporal Yield Variability under Long-Term Manure and Fertilizer Application: Fractal Analysis

B. Eghball,* G. D. Binford, J. F. Power, D. D. Baltensperger, and F. N. Anderson

ABSTRACT

Long-term experiments offer unique possibilities to study the effects of management practices on crops and soils with time. Characterizing temporal variability of grain yield provides an opportunity to distinguish between the effects of environment vs. management practices on grain yield, an important parameter. A long-term study was established in 1912 in western Nebraska as part of a rotation study. In 1953, each plot was divided into manure (27 Mg ha^{-1} annually) and no-manure sections to which fertilizer treatments of 0, 45, 90, 135, 180 kg N ha^{-1}, and 135 kg N + 80 kg P ha^{-1} were applied annually. Grain yield data from 1953 to 1993 for these treatments were used for fractal analysis and determination of fractal dimension (*D*), which is an indication of pattern of variation. A *D* value close to 1 indicates dominance of long-term variation (or trend), while a *D* value close to 2 indicates dominance of short-term (year-to-year) variation. Grain yield increased with increasing N application rate without manure, but no response to fertilizer application was observed where manure had been applied. Fractal dimensions ranged from 1.942 to 1.996, indicating significant domination of short-term variation of grain yield in the past 41 yr in all treatments. There was no significant difference between *D* values for manure or fertilizer treatments. Soil fertility amendments did not alleviate year-to-year variability observed in the corn (*Zea mays* L.) yield. Environmental factors like hail, fall freezing, and temperature variation during the growing season had a significant effect on the grain yield over the years. Although management practices can reduce temporal grain yield variability in some crops, variations in environmental factors in this study were great enough to dominate the yearly maize grain yield regardless of soil fertility amendments.

Long-term studies offer unique opportunities to evaluate the influence of certain long-term management practices on crop yield and soil properties with time. Long-term field research can be especially useful in developing and validating crop simulation models (Acock and Acock, 1991). Well-summarized data from long-term cropping systems can give agriculturalists and others direction for improvement and sustaining productivity in a cost-effective manner while recognizing environmental concerns (Cady, 1991). Long-term field studies are essential to the development of sustainable agricultural systems because they are a primary source of scientific knowledge about agronomic conditions during the long period of farming (Sandor and Eash, 1991).

Fractal analysis, which is based on self-similarity (the manner in which a pattern at one scale is repeated at other scales), has been useful in characterizing plant and soil parameters. In fractal analysis, the fractal dimension (*D*), which as the name implies, can be fractional, need not be an integer, and is scale independent. It is an indicator of the shape (geometry) of the fractal parameter being studied. Eghball et al. (1993) used the fractal dimension to statistically compare treatments that influenced the morphology of corn roots. For spatial and temporal variability, *D* can range from 1 (values within spatial and temporal range of analysis fall on a line) to 2, which indicates so much variation that an entire two-dimensional surface is covered by the range of variation. Large *D* values indicate the importance of short-range variation, while small *D* values reflect the importance of long-range variation.

Temporal variability is an important factor to consider when evaluating the performance of long-term experiments. Fractal analysis can be used to distinguish between short-term and long-term variations for parameters collected in time or space. Eghball and Power (1995) used fractal analysis to characterize temporal variability for average yield of 10 crops in the USA with a wide range of yield levels and found that crops were significantly different in terms of temporal variability. They observed less year-to-year grain yield variability for rice (*Oryza sativa* L.) than other grain crops, which was judged to be due in part to management practices commonly used for this crop.

Manure application can improve soil chemical and physical properties. Crop grain yield response to manure application, a source of macro- and micronutrients, is positive (Magdoff and Amadon, 1980; Mathers et al., 1975). Temporal variability of grain yield of crops that have received manure or fertilizer application has not been characterized. There is a need to establish whether temporal variability is due to certain management practices or environmental factors. The purpose of this study was to characterize temporal variability of maize grain yield from a long-term study of manure and fertilizer applications using fractal analysis.

MATERIALS AND METHODS

An area of native sod near Mitchell, NE was first plowed in 1910, and in 1912, a nonreplicated rotation study was initiated. Two of the initial rotations in the study have been combined over the years to form what is now a fertilizer rate-manure continuous corn study with two replications. Replication 1 of the current long-term study was in continuous corn with no fertilizer or manure applications from 1912 to 1941. In 1942, this replication was split into two plots, with one-half of the plot receiving an annual application of cattle (*Bos taurus*) feedlot manure (27 Mg ha^{-1}, wet basis), while no manure was applied to the other half. In 1953, the manure and no-manure plots were split again into six subplots. Each subplot received annual fertilizer treatments of 0, 45, 90, 135, 180 kg N ha^{-1}, and 135 kg N + 80 kg P ha^{-1}. Replication 2 of the current long-term study contains the same fertilizer and manure treatments as Replication 1 and was initiated in 1953. Replication 2 area was in a sugarbeet (*Beta vulgaris* L.)-potato (*Solanum tuberosum* L.) rotation and received a biennial application of

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Table 1. Average grain yield of corn (CV† = 30.5%) under different manure (27 Mg ha^{-1}, wet basis) and fertilizer applications from 1953 to 1993 in Mitchell, NE.

Fertilizer	Manure	No manure
kg ha^{-1}	Mg ha^{-1}	
0	5.73	2.03
45 N	5.99	3.81
90 N	5.91	4.97
135 N	6.17	5.34
180 N	6.04	5.64
135 N + 80 P	6.03	5.54

† CV = coefficient of variation.

cattle manure (27 Mg ha^{-1}) from 1912 to 1949. The study has been in its present treatment structure since 1953. Ammonium nitrate was used as the N source and triple superphosphate (0-20-0, N-P-K) was used as the P source. Fertilizer and manure were broadcast each year in the spring prior to planting. The area has been furrow irrigated, five to seven times each year, depending on crop water needs. Additional information regarding this experiment can be obtained from Anderson and Peterson (1973).

Grain yields were measured by hand harvesting a center portion of each plot. The manure has come from the same feedlot every year, and there have been no major changes in the feed rations or in methods of handling the manure during the last 25 yr (I. Rush, 1994, personal communication).

Fractal analysis was performed on the maize grain yield of different manure and fertilizer treatments based on the method described by Eghball and Power (1995). Briefly, semivariances were calculated for grain yield of all plots from 1953 to 1993 based on the method described by Clark (1979). Analysis of covariance was performed on the data to estimate the slopes and also to determine the differences between the slopes of the regression lines for different treatments. Regression of log semivariance vs. log year (lag) for each treatment provided an estimate of fractal dimension [$D = (4 - \text{slope})/2$]. Grain yields from 1968 and 1981 were not included in the analysis because of complete loss due to hail and technical error, respectively. Thirty lags were used for determination of D to ensure an adequate number of squared differences. Since the slopes and D values are related by constants, the differences between slopes reflect differences between D values. Semivariances were calculated using a FORTRAN computer program, and SAS was used for the covariance analysis. The yield data for each treatment were also standardized to a mean of zero and unit variance based on the following equation given in Eghball and Power (1995):

$$\text{SV} = (Y - \mu)/\sigma \qquad [1]$$

where SV is the standardized value, Y is the yield level, μ is the mean, and σ is the standard deviation. Standardization was done to remove the yield level differences between treatments so that they can all be evaluated on the same scale. A probability level of $P < 0.05$ was considered significant.

RESULTS AND DISCUSSION

Grain yields tended to decline during the first 30 yr after initiation of the study (1912–1941) because there was no fertilizer or manure applied during that time (data not shown). During the 1940s, grain yields tended to increase due to initiation of the manure treatment and introduction of hybrid corn. There was a manure × fertilizer interaction for grain yield ($P < 0.01$) based on the analysis of variance. Grain yield increased with increasing fertilizer N rate in the absence of manure, but there was no effect of fertilizer application on grain yield in plots receiving manure (Table 1, Fig. 1). The slope of the regression line relating grain yields to amounts of fertilizer N applied on the manured plots was not statistically different ($P > 0.05$) from zero. A

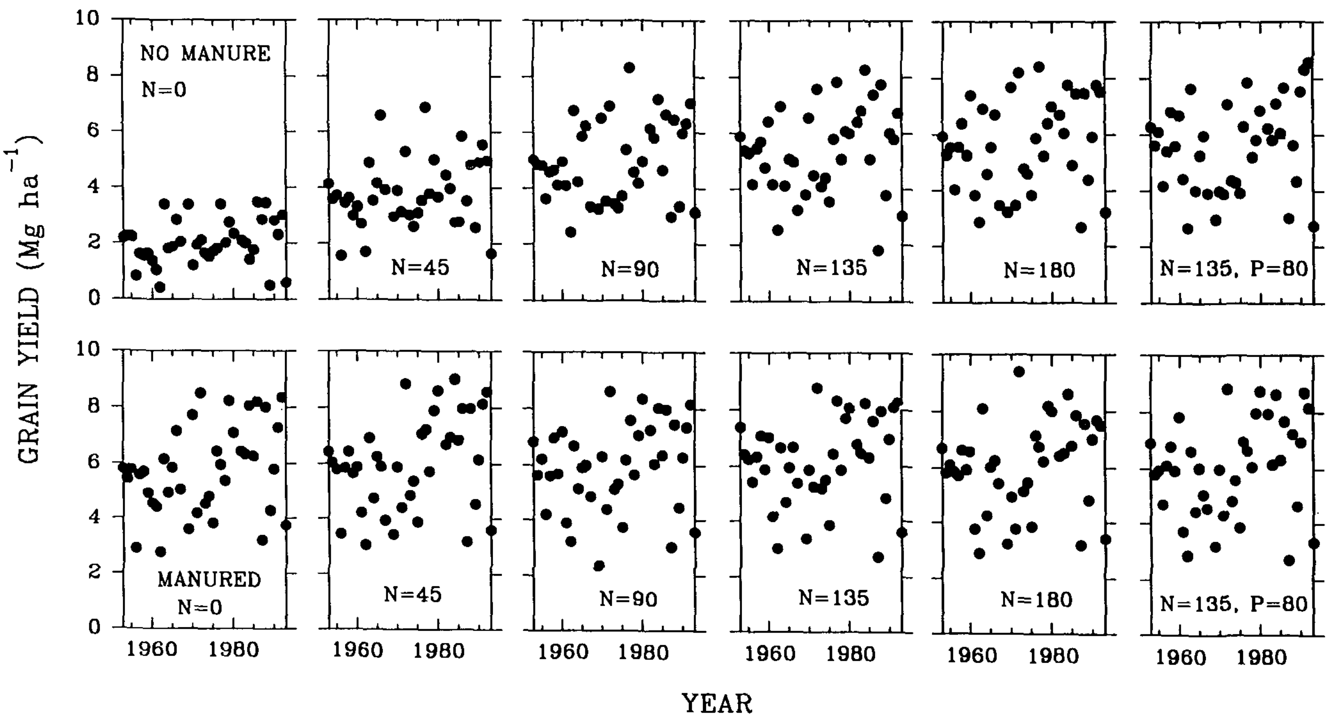

Fig. 1. Corn grain yields for different manure and fertilizer treatments from 1953 to 1993 at Mitchell, NE.

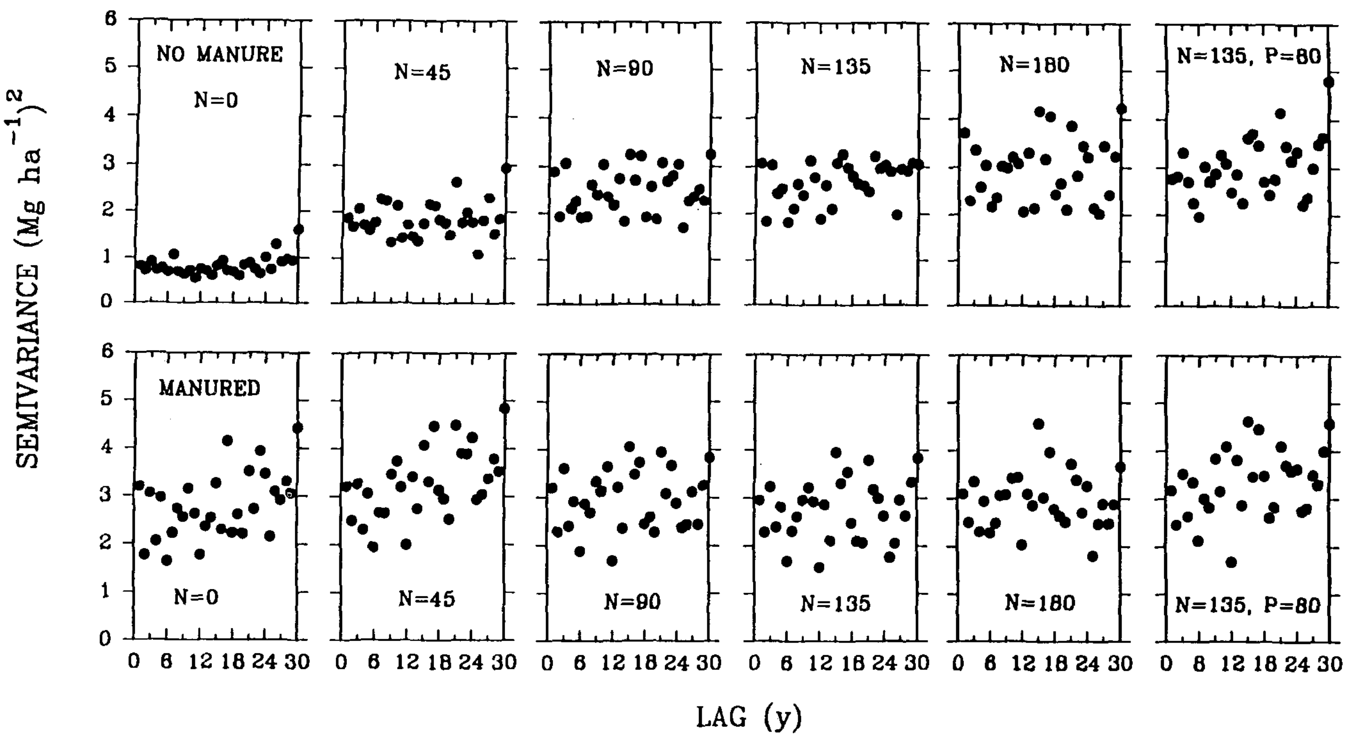

Fig. 2. Semivariance values for grain yield of corn for various manure and fertilizer treatments at Mitchell, NE.

yearly application of 27 Mg cattle manure ha^{-1} was sufficient to obtain near-optimal grain yields of corn. The average yield of the manured, nonfertilized plots was 3.70 Mg ha^{-1} greater than the average yield of the nonmanured, nonfertilized plots from 1953 to 1993 (Table 1).

Semivariance values for manure and fertilizer treatments are given in Fig. 2. Results of the analysis of covariance (R^2 = 0.70, $P < 0.01$) are reported in Table 2. Manure, fertilizer, and manure × fertilizer indicate effects of these variables on semivariances. Interaction of manure, fertilizer, and manure × fertilizer with log year indicate differences between the slopes ($4 - 2D$) of regression of log semivariance with log year. A D value close to 1 indicates domination of long-term variation (or *trend*, which is a long-term variation) whereas a D value close to 2 indicates so much variation that basically a whole two-dimensional surface in the x-y plane will be covered by the extent of variability (strong domination of short-term variation). There was no significant difference between D values for manure and no-manure treatments. The D values were 1.971 for manured plots and 1.981 for no-manure plots (Table 3), indicating a strong dominance of short-term variation in both treatments with no apparent long-term trend. The D values for fertilizer treatments ranged from 1.958 to 1.996 with no significant difference between them (Tables 2 and 3), also indicating significant short-term variation for these treatments.

Manure application with or without fertilizer application apparently did not alleviate temporal corn yield variability in this experiment. This year-to-year fluctuation is primarily a result of variable weather. This area of Nebraska has one of the highest frequencies of hail in the USA. Also, early fall freezes, which reduce the yield potential of corn, tend to be more common in this

Table 2. Analysis of covariance (R^2 = 0.70) for semivariances of corn grain yield from 1953 to 1993 at Mitchell, NE.

Source of variation	df†	Probability level
Replication	1	0.02
Manure	1	0.41
Replication × manure‡	1	
Fertilizer	5	0.01
Manure × fertilizer	5	0.01
Log year (lag)	1	0.01
Log year × manure	1	0.85
Log year × fertilizer	5	0.31
0 N vs. 180 N§	1	0.06
45 N vs. 90 N	1	0.25
135 N vs. 135 N + 80 P	1	0.41
Log year × manure × fertilizer	5	0.69
Error	694	

† df = degrees of freedom.
‡ Replication × manure was used as an error term for manure and log year × manure.
§ Contrasts comparing the slopes.

Table 3. Slope of regression line of log semivariance vs. log year (lag) for grain yield of corn from 1953 to 1993 and fractal dimension (D).

Source of variation	Slope	D
Manure	0.059	1.971
No manure	0.038	1.981
Standard error of estimate	0.016	
Fertilizer treatments, kg ha^{-1}		
0	0.083	1.958
45 N	0.064	1.968
90 N	0.018	1.991
135 N	0.042	1.979
180 N	0.008	1.996
135 N + 80 P	0.075	1.963
Standard error of estimate	0.028	

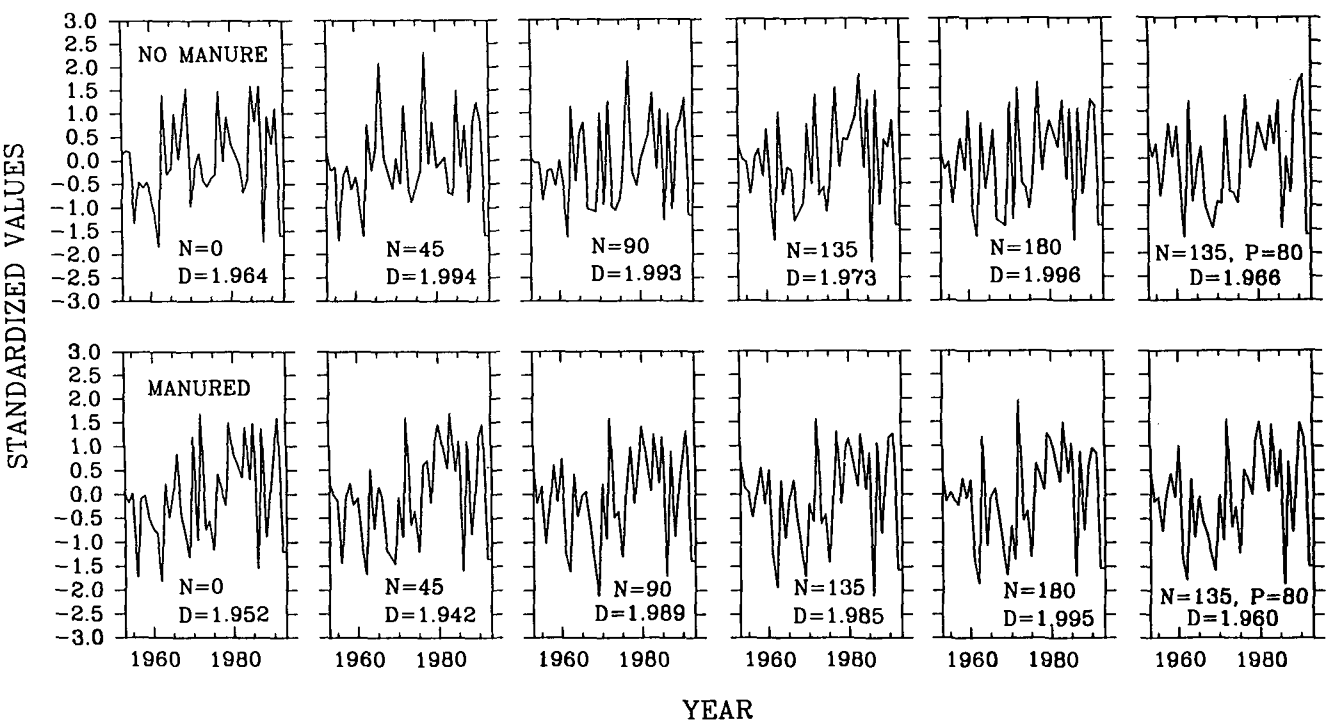

Fig. 3. Corn grain yields standardized to a mean of zero and unit variance for different manure and fertilizer treatments from 1953 to 1993 at Mitchell, NE.

region than in most corn-growing areas because of the high elevation (≈ 1200 m). Although in-depth weather data have not been recorded each year for this study, it is known from long-term weather records at this research center that early fall freezes occurred in 1962, 1968, and 1993. Grain yields were quite low in all of these three years. In 1968, the crop was a complete loss due to hail damage, and we know that significant hail damage also occurred in 1987, 1989, and 1993, which were also low-yielding years.

Environmental conditions at any location influence crop growth and subsequently grain yield. Management practices may in some cases reduce temporal variability (Eghball and Power, 1995), but in other cases, management practices have little effect on the year-to-year variability of crop yields. Standardized yield levels for different treatments in this study indicate little effect of soil fertility treatments on the variability of corn yield (Fig. 3). Standardization enables us to compare treatments with different levels of grain yield. Grain yield peaks and lows were consistent in all treatments (Fig. 3), indicating once again the strong influence of environment on corn grain yield. In these environments, because of the highly variable weather that prevails, it may be difficult to predict crop yield with time and model the temporal plant growth.

To evaluate the advantages of fractal analysis, it is useful to compare it with standard regression analysis. In the fractal analysis, since D values are scale independent and do not depend on the yield levels but rather on variability, they can be compared between crops and treatments that have different yield levels. Standardizing the yield levels using Eq. [1] produces data sets with similar linear slopes for all treatments. Also, dominance of short-term (year-to-year) vs. long-term (trend) variation can be determined for each treatment using fractal analysis. Eghball and Power (1995) showed significant differences between 10 crops for yield variability during 61 yr, even though regression analysis indicated an increase in yield with time for all crops. They indicated that oat (*Avena sativa* L.) and soybean [*Glycine max* (L.) Merr.], which had the greatest short-term variation in the fractal analysis, had two of the lowest coefficient of variation values in the regression analysis.

CONCLUSIONS

Fractal and covariance analyses were good methods of characterizing and comparing temporal corn grain yield variability for different manure and fertilizer treatments. By using fractal analysis, it was possible to determine if short-term (year-to-year) or long-term variation dominated the grain yield of corn in a period of 41 yr. Temporal variability of corn grain yield was greatly influenced by environmental conditions as the short-term variation dominated for all treatments. Long-term manure and fertilizer application did not alleviate the year-to-year variability. It seems that management practices could not alter the strong influence of variable environmental conditions in areas similar to western Nebraska.

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